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KNOCKING IN THE OTTO-CYCLE ENGINE

By H. Weinhart

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INTRODUCTION

Attempts to improve the thermal efficiency of Otto-cycle engines through raising the compression ratio meet - in the appearance of knocking - an as yet insurmountable obstacle. While in the past the knocking was ascribed to the contact of metal parts, it is now generally conceded to be a combustion phenomenon. Knocking is associated with a decrease in power and high local combustion pressures which are a potential source of damage to the engine.

Research originally developed two fundamentally different theories of the combustion of knocking engines. One theory believes that the residual charge, almost adiabatically compressed by the first combustion, reaches such high temperature that autoignition takes place. This cause of origin of knocking is termed "pressure ignition." A second theory assumes that the favorable combustion conditions can create a detonation wave in the residual charge which passes through it with its characteristic speed of around 2,000 meters per second and, on hitting the cylinder wall, causes the knocking noises.

HISTORICAL DISCUSSION

The earliest experiments on engine knock were restricted to measurements of knock intensity. Thus Midgley and Boyd (reference 1) employed a so-called "bouncing pin" to measure the time interval during which a certain maximum pressure in the cylinder is exceeded as criterion for the knock intensity. It is to Midgley's special credit to have discovered the knock inhibitors which even today remain an indispensable auxiliary in high-speed engines.

*"Das Klopfen im Otto-Motor." Luftfahrtforschung, vol. 16, no. 2, February 20, 1939, pp. 74-83.

Ricardo (reference 2) carried out elaborate studies on his engine with variable compression ratio and determined the compression ratio at which the most dissimilar kinds of fuels still assured normal combustion. Systematic studies of combustion-chamber forms disclosed that long and divided chambers have a special tendency to knocking, while the pent-roof contour proved the most propitious.

That the results obtained on a knocking engine did not lend themselves summarily to generalization, is indicated by Dumanois' experiments (reference 3). Dumanois was able to raise the compression ratio in his test engine from 4.6 to 6.7 before knocking took place, after replacing the standard piston by a stepped piston. His explanation is that the explosion wave, which he considers the cause of knocking, is either prevented by the sudden pressure drop or destroyed at its presence.

Wheeler, Lovell, Coleman, and Boyd (reference 4) took samples at various crank angles during the combustion for analysis as to the content of water vapor, carbon dioxide, carbon monoxide, hydrogen, and oxygen. They found a consistently increasing content of combustion gases in the samples at crank angles above 40°. These findings are in contradiction of the assumption of a flame starting at the point of ignition and shooting through the combustion chamber.

A number of studies concerned the type of combustion in bombs. The earliest experiments are those by Mallard and Le Chatelier (reference 5), and subsequently supplemented by Dixon's classic experiments (reference 6) with improved equipment. They originally proved by direct photographs the explosion wave with all its typical characteristics. In connection herewith the work of Nägel (reference 7) on the rate of ignition of explosible gas mixtures, the experiments by Klüsener (reference 8) on the effect of turbulence on the rate of combustion, and the work of Dumanois and Lafitte (reference 9) regarding the effect of pressure on the entrance length of explosion waves, deserve special mention.

Endres' theoretical study of the combustion cycle (reference 10) is a further contribution to the problem of knocking; he found a relation between combustion-chamber form and knock tendency.

Callendar (reference 11) is of the opinion that the compression and heating associated with it might cause a chemical change and a sudden decomposition of the charge, through which knocking is caused.

Auer's experiments (reference 12) were particularly valuable. He studied the intensity and the moment of knocking, using the forces of acceleration imparted by the gas pressure on a spring-loaded piston in the cylinder head as criterion of the intensity. The relation of the measured quantities with the r.p.m., the compression ratio, temperature of inducted air, moment of ignition start, and air-fuel ratio, is shown. The maximum knock intensity occurs at that air-fuel ratio which gives the minimum time between the ignition and the shock. Hence the closer the shock occurs at dead center, the greater is its intensity. A change in compression ratio has the greatest effect on the knock intensity.

Richter (reference 13) has collected the scattered data on knocking into a comprehensive report, while Lindner (reference 14) gives a comprehensive compilation of data on the ignition and combustion in gas mixtures, along with a brief discussion of the most important research work.

But in spite of this wealth of data, it afforded no clue to the nature of the knock; none of the works could decide whether the explosion wave or the pressure ignition caused the knocking.

Deeper insight was finally afforded through Schnauffer's study of flame propagation in the knocking engine (reference 15). His findings were briefly as follows: In the nonknocking engine the flame passes through the combustion chamber at about constant speed. (See reference 16, also.) At detonation, the last part of the mixture is simultaneously ignited, causing high local temperature and pressure rises, whereas for normal combustion, a pressure balance always exists as a result of the lower combustion rate. The violence of the knock depends on the amount of simultaneously ignited residual charge. Knocking is associated with a rise in ionization and a decrease in the late-burning period. If the combustible mixture ignited simultaneously is very great, the heat expansion of the burning mixture causes a negative flame speed. If the engine has detonated for some time, such negative flame speeds are also observable; they are caused by the ignition of the combustible charge at the hot parts of the engine. There are four types of knock which are distinguished by the pressure changes that occur.

In a later report (reference 17), Schnauffer increased the number of test tubes to 24 and recorded the ionization current through illumination of 24 glow lamps with a specially designed short-period recorder. The direction and speed of flame motion under normal engine operation was ascertained under the most diverse test conditions. These tests disclosed very plainly the effect of the hot exhaust valve, the spark-plug arrangement, and the load changes on the form and speed of flame movement. While in normal operation the speed of the flame front remained nearly constant over the entire combustion chamber, the residual charge disclosed a speed of from 265 to 300 meters per second by knocking operation. The order of magnitude of this speed manifested that no detonation wave was present as combustion form.

The United States also has done extensive detonation research for years, which has culminated in a report by Withrow and Rassweiler (reference 18). These research workers covered the whole combustion chamber of an Otto engine with a quartz window, and took high-speed motion pictures at 5,000 frames per second. Thus, while the earlier results regarding form and speed of flame front could be confirmed, they disclosed in the detonating end gas newly developed ignition centers independent of the old flame front. From these centers the ignition spreads nonuniformly and with marked change in form and magnitude over the unburned part of the charge.

Contemporarily, Sokolik and Voinov (reference 19) also proved the explosion wave in the detonating engine by direct photography. They employed the Mallard-Chatelier method - i.e., starting at the spark plug in the cylinder head, they fitted a small quartz window across the whole combustion chamber through which they took the flame pictures. The combustion rate in the residual charge recorded at 2,000 meters per second, agrees with the detonation velocity of an air-fuel ratio theoretically computable by Jouguet's method (reference 20).

A number of investigations deal with the pressure in the combustion chamber. Since the combustion speed in the residual charge is, in any event, extremely high and a pressure equalization can be no more than partially complete within this short period, a zone of high pressure - originally pointed out by Schnauffer (reference 15) - is built up which then flows off in the form of a shock wave and is reflected repeatedly on the walls at consistently lower amplitudes. The resulting stationary waves in the combustion chamber have been proved piezometrically by Boerlage, Broeze, van Driel, and Peletier (reference 21). In very long test bombs, gas vibrations occur also at normal combustion; this noise is not to be confused with the distinctly different hard, clear note of the detonation noise in the knocking engine or detonating gas mixture.

The decrease in power and the rise in cooling-water temperature then are the result of increased heat transfer to the wall because of the high flow velocities of the hot combustion gases due to the oscillation relative to the wall and the higher pressure at the vibration peaks.

The literature itself affords no uniform concept of the nature of knock, nor of the combustion rate in the detonating residual charge. So in view of the importance attaching to the safe knowledge of the type of combustion for the whole engine design, an attempt was made to make a new contribution to this problem with the most modern pressure-recording equipment and by a different method. This method is the now almost perfect piezoelectric pressure-recording method in conjunction with a novel application of the ionization method for recording combustion in the detonating gas portion. The potential use of the ionization method for recording temperatures in the combustion chamber had previously been pointed out by Schnauffer (reference 16).

Strictly speaking, the conclusions drawn from the present study apply only to the explored engine; for very dissimilar engine-design types, other results might be obtained.

ORIGINAL TESTS

a) Test method.- In order to be able to differentiate between pressure ignition and detonation wave at combustion in the detonating engine, the quantities especially typical for these two types of combustion must be recorded.

For a detonation wave (= discontinuity wave at the front of which combustion takes place), the combustion occurs in an extremely small flame front, whose thickness is about equal to the free path length of the molecules (references 20, 22). The speed of this flame front is a quantity peculiar for each gas mixture, almost independent of the test conditions. The pressure wave initiates the ignition. The temperature in the flame front is slightly higher than in the loss-free isochoric combustion. When the detonation wave has reached a volume particle, the combustion in it will be terminated within an almost infinitely short time; i.e., temperature change is abrupt. During reflection of a pressure wave on a rigid wall, its kinetic energy changes temporarily to pressure, which numerically is equal to twice the wave momentum (reference 23).

For the stoichiometrical benzol-oxygen mixture, a detonation speed of 2,440 meters per second, a pressure increment in the wave equal to 43 times the initial pressure, a flame-front temperature of 6,295° C., and a pressure equal to 160 times the initial pressure during the reflection, was computed.

In pressure ignition the mixture must be brought, by a compression without substantial heat removal, to a temperature higher than the autoignition temperature, so that spontaneous ignition takes place after a short period. By autoignition temperature is meant the temperature limit at which, under the present test conditions, the released heat volume of the chemical reaction already taking place at these low temperatures, is exactly as great as the heat losses. Mathematically, the autoignition temperature is the temperature limit for infinitely great ignition lag; for upon completed compression, a finite time lapse (ignition lag) passes before ignition starts. The ignition lag is dependent upon the temperature rise over the autoignition temperature. In a volume element the temperature rises steadily up to its maximum because the speed of reaction rises steadily with increasing temperature, and the heat volumes released by chemical reaction, are at first small.

Three particularly appropriate characteristics were included for comparison. Normal combustion in the bomb is compared with the normal operation in the engine, and detonation in the bomb with the engine knock. It should follow that:

1. The pressure measurement will indicate a directed pressure wave only during detonation.

2. During detonation the electric-ionization current in the test plug (as function of the reaction process) reaches its maximum value by increments.

3. The flame velocity differs during detonation in orders of magnitude from normal burning and is immeasurable in pressure ignition.

b) Experimental arrangement.- The test bomb consisted of a seamless steel tube (fig. 1) 1 meter long, 2-inch inside diameter sealed with two blind flanges threaded to receive, respectively, the quartz chambers and the ionization test plug. To assure a homogeneous air-fuel mixture, the combustion air was saturated in a saturation tank (fig. 1) with fuel at higher pressure and constant temperature (fig. 1) and then throttled. This method proved very practical and afforded at any time, reproducible and very uniform mixture ratios by changing the pressure and temperature in the saturation apparatus. The mixture composition was checked by exhaust-gas analysis.

For the pressure measurement, a BMW-VI airplane-engine cylinder on a single-cylinder test stand was available (n = 1,800 r.p.m., N = 50 hp.; ϵ = 1:3 to 1:8). A piezo-electric engine indicator with a two-way oscillograph and two built-in amplifiers recorded the pressure. The time constant of the initial circuit for the employed test range amounted to more than 1 minute. The recording was made on a drum camera with a 1:2 lens. One quartz pick-up unit was of special design with an unusually high natural frequency; the light-metal diaphragm had a free diameter of 25 millimeters. It was put to within 4 millimeters of the combustion chamber. It was completely free in front (fig. 1). The two piezo-quartz pieces were of 20-millimeter diameter, and as flat as possible. The natural frequency of this unit was so high as to preclude excitation to periodic oscillation by striking with a hammer, since the hammer returned aperiodically to zero position with the diaphragm.

c) Pressure measurement in the bomb.- After verifying the proper working of the equipment, pressure-time records were taken at both ends of the bomb with hydrogen-acetylene and fuel-air mixtures at normal combustion, the mixture composition and the charging pressure being varied. Ignition took place on top; the timing is indicated on the records with z. Figure 2 illustrates the pressure-time record of a normally burning hydrogen-air mixture as taken simultaneously at the two test points. The pressure curve at the upper test point (next the spark plug) discloses, shortly after completed ignition, a steady and slow pressure rise. Even during this time interval a very potent pressure wave already reaches the lower test point, where it is reflected back and rushes through the pipe toward the flame. For very rich mixtures and at low charging pressures, this pressure disturbance has as yet no steep front and so passes through the pipe with a velocity which approximates that of sound. It sped ahead of the much slower flame front. With the flame, it builds up a new pressure wave which already is much steeper and, together with the flame, reaches the end of the pipe (M in fig. 2). An ionization-current measurement at the end of the pipe confirmed this coincidence.

The second pressure change is already so steep that the upper piezoelectric chamber (normal engine chamber) is excited to natural oscillations (about 20,000 Hz). At higher charging pressures or with leaner mixtures, these interference waves become more and more pronounced, and the pressure-time records assume a form shown in figure 3. Since disturbances with great pressure jumps propagate substantially faster than at sonic velocity (reference 23), that with the flame will soon outdistance all preceding smaller disturbances. The pressure jump has then become so great that the conditions for release of a detonation wave are at hand. The record of a detonating hydrogen-air mixture is then as in figure 4, where the lower test point before arrival of the detonation wave fails to disclose the least sign of pressure disturbance. From the mean combustion period, compared with figure 2, it is apparent that the detonation wave must have been created at half distance. It also is seen that, up to the first return on the lower test point corresponding to the greater rate of propagation, a shorter time period passes. The measured pressure jump amounts to 270 atmospheres for an initial charging pressure of 8 atmospheres. Even though this result is quantitatively too low, inasmuch as with such rapid pressure changes, even the piezoelectric indicator itself fails in its low inertia, the obtained cards are nevertheless valuable qualitatively. Perhaps the theoretically computed pressure does not actually occur, since at such high-pressure changes the quartz chamber is no longer rigid enough to satisfy the assumptions made for the pressure prediction. Whereas normal combustion was accompanied by a dull hum, detonation manifested itself by a clear, hard blow; hence the suspicion that these noises are identical with the engine knock.

Another fact worth noting is that, during these bomb tests the standard spark plug fitted at the lower end of the pipe for purposes of temporary closure of a second hole, failed to withstand the stress and consistently blew out the insulating body from the casing. But, since, on the other hand, the charging pressure in the bomb tests is comparable with the terminal compression pressure in the engine, the destruction of the spark plugs alone might raise justifiable objections as to whether the detonation is synonomous with the knock. For purposes of studying the effect of combustion-chamber design on the formation of detonation waves, Wentzel's spherical bomb with central ignition (reference 24) was used to burn hydrogen-air mixtures at different charging pressures. It was impossible to reach detonation even at higher pressures than in the test pipe - a fact which is in accord with Jouguet's theoretical studies (reference 20), wherein it is proved that the detonation wave is bound to a flat flame front. As easy as it is to produce detonation in the test pipe with all oxygen mixtures, it was just as hard with gas-air mixtures. With hydrogen, it required charging pressures of over 5 atmospheres; or less if a screen was fitted at half pipe length. It was originally believed that this would act as an effective damper of the vibrations in the pipe and so, according to Nielsen (reference 25), reduce the combustion rate substantially. But why - through this damping - the release of the detonation wave was enhanced, lacks, for the time being, every potential conception. The screen, originally of wire mesh, was subsequently replaced by a steel plate with 4-millimeter holes. It was only usable for one test because it was knocked through in flame-advance direction; screens over 2.5 millimeters thick were not destroyed, but even they were considerably buckled. The sense of the destruction seemed to indicate that the detonation wave originated below the screen and caused the destruction after completed reflection at the lower end of the pipe. The detonation records for all employed mixtures are qualitatively identical. This included tests with detonating gas, acetylene, benzol-oxygen, and hydrogen-air mixtures.

d) Pressure measurement on the engine.- The same quartz chamber and the same oscillograph were next used for the pressure measurements on the BMW-VI airplane engine under widely varying r.p.m. charge, fuel, and compression ratio. The records made at violent knock indicate a maximum pressure of only about twice the normal combustion pressure (fig. 5).

Although these tests were made with the diaphragm almost at the combustion chamber and so, almost in the continuation of the cylinder wall, these measurements are still open to the objection that the diaphragm was never parallel to the flame front of a possibly produced detonation wave, thus making it possible to measure the existing maximum pressure which, according to theory and bomb studies, should exceed the recorded double value very substantially. Changing the position of the spark plug, of the r.p.m., the mixture composition, the compression ratio, etc., themselves, yielded no different results, although it might have been probable that by one of these acts the wave front did assume the correct position relative to the quartz chamber. But the uncertainty still afflicting this test method prompted further measurements in the interest of elucidation of the posed problem.

e) Ionization current change and flame speed.- These engine tests were carried out on a single-cylinder Baumann engine (fig. 6: $n = 300$ r.p.m., $N = 8$ hp., $\epsilon = 1:6$; bore = 165 mm, stroke = 180 mm) which, because of its adaptability for mounting the test plug, was particularly suitable for the purpose. It is the same engine used by Auer (reference 12) for his knock experiments.

1. Test Circuit

The arrival of the flame front at the test point was recorded by ionization method (Kuchtner, Schnauffer, references 26, 15), the ionization current being recorded by cathode-ray oscillograph and camera. The test plug itself (figs. 1 and 6) consisted of three electrodes with insulating bodies (3 mm sintercorund shell), extending 7 to 8 millimeters into the combustion chamber; the test length was 5 millimeters. The temperature of these electrodes was so high as to burn off the soot on the insulating shell. To check the effect of the hot test plug on the test procedure, one electrode with the same outside dimensions was fitted with a constantan wire, the other with a copper wire. Then the wires were bent together and hard-soldered. The highest temperature of the electrodes was measured with this thermocouple and compared with Schnauffer's record obtained for a special plug in the engine (reference 27). It was found that at normal operation the temperature in relation to load and excess air, ranged between 330° and 420° C., and first rose to beyond 1,000° C. after detonating operation of more than one minute. In spite of that, nothing unusual was observed on the running of the engine during the last test. Hence, it is safe enough to assert that in normal engine operation, the danger of test plug affecting the combustion is nonexisting as its temperature remained much below 800° C. This temperature difference is really even greater since the employed millivolt meter indicates only the mean value over a period, and the test plug has its minimum temperature near the instant of ignition.

The voltage of the test length was 140 V, the resistance in the voltage input, 1 M Ω (0.1 M Ω in the bomb detonation tests) (fig. 7). The oscillograph deflections are therefore proportional to the ionization current. The maximum current is 140 (1,400) μA. For a deflection response of the cathode-ray oscillograph of 0.17 mm/V (AEG-two-ray tube with after acceleration), it yields a test circuit response of 0.17 mm/μA ionization current. In a contemporary research report (reference 28) on a two-stroke Diesel engine, even the use of a voltage amplification of 200 failed to disclose any effect of the terminal compression temperature (about 600° C.). The sensitivity of this test arrangement was 30 mm deflection/μA. These experiments lead one to conclude that only the strong ionizing effect of the flame, or else the free ions during a chemical process, are in a position to carry perceptible currents into such a test circuit and so cause a visible deflection.

2. The Time Circuit

The highest permissible film speed with respect to photographic recording was about 8 meters per second if superposed by a rapidly changing process. This film speed, however, was insufficient for ionization-current measurements and made ordinary photographing necessary. The moving film was therefore replaced by a photographic plate, the points on the light screen being perpendicularly deflected to the test deflection with respect to time. This was accomplished by connecting the deflection plates for the time deflection on the oscillograph to a condenser charged over a resistance from a constant voltage source. The voltage on this condenser rises with time according to an exponential function, and so deflects the points on the light screen accordingly. The advantage over high film speed is that then a photographic record of 500 meters per second is possible (the AEG quotes 10 km/s for a lens 1:1), since the luminous substance of the fluorescent screen remains photographically active about 1/5 second afterward;

that is, after completion of the actual test procedure. The deflection plates of the time circuit (fig. 7) are hooked up to a condenser C loaded over resistance R under tensile strain. The velocity of the point drops linearly with the path, so the time scale becomes logarithmic. The time interval between two settings of the point on the screen (or on the photograph) is $RC(\ln u_1 - \ln u_2)$ in seconds, if u_1 and u_2 are the deflection voltages coordinated to the settings, and RC is the time constant of the time circuit. The condenser is kept discharged by a Thyratron (grid-controlled vacuum tube) if its grid with the cathode has the same potential. The stabilizer at first is not ignited. On this stabilizer is impressed, across a resistance W, a voltage approximating the ignition voltage. The glow surfaces absorb their partial voltages even before any measurable current is passed through the stabilizer. As soon as this potential distribution is then disturbed, the ignition voltage is exceeded at one of these surfaces and the ignition of the whole stabilizer initiated. This disturbance may, for instance, be induced by grounding one of these glow surfaces (across a protective resistance) or, with capacity coupling, by a change in voltage at the coupling condenser. In the present experiments, one of the surfaces was galvanically joined to the first electrode of the test plug (release electrode). If the advancing flame then strikes the electrode the ground across the flame of the stabilizer is ignited and the Thyratron cut off through the voltage drop at the resistance W in the cathode line; so that the charging of condenser C can begin. Thus, with proper magnitude of R and C, recording speeds ranging from a few centimeters per second to several kilometers per second can be obtained. The process of ignition and hence the deflection repeats itself only when the switch S is briefly opened. The contact resistance across this switch is intended to assure that the glow surfaces have absorbed their proper voltage before closing - while the resistance is chosen great enough to extinguish the stabilizer. This hook-up not only assures a unique time deflection but also a release of the time circuit with a few volts and with currents of the order of magnitude of 1 μA; a power input considerably lower than by influencing the grid on the Thyratron direct. A very exact time release was necessary because the time available for measuring with a point velocity of 200 meters per second and a light screen diameter of 5 centimeters is only 1/4000 second. On that account, the release ~~from~~ the flame itself had to be controlled, since its arrival at the test length in the engine or in the bomb could not be predicted with such accuracy, nor did it remain constant from one test to the next.

3. Normal Combustion in Bomb and in Engine

With the foregoing arrangement the ionization-current change was recorded for bomb combustion of hydrogen-, acetylene-, gasoline-, and benzol-air mixtures (fig. 8). The two deflections in figure 8 indicate the current distribution of the two test plugs. The diagrams were similar for the employed gas mixtures and, with test length known, permitted the determination of the flame speed. It also discloses the change in ionization current and its maximum amount of change. The same fuels gave in engine operation at normal combustion, a current distribution as indicated in figure 9. This test series was made with the same time scale as the corresponding bomb tests. The flame speeds obtained therefrom in the engine were scattered from 3 to 20 meters per second, and were dependent upon the load and the excess of air. The wide scattering (of more than 100 percent) was to be expected with the shortness of the test length (5 mm), since any averaging is lacking and even a directional change in flame front is followed by an apparent rise in speed. At lower load or great excess of air, the scatter was even more pronounced, since the turbulence in conjunction with the lower flame speed causes a partial release of the flame front.

The ionization-current change, on the other hand, showed no difference. The slow current rise, like a slow temperature rise, agrees with the concept that during combustion the activation energy from layer to layer is largely transmitted by heat conduction and, on reaching the autoignition temperature in this layer, a continuously faster chemical reaction begins. This concept of the combustion process was taken from Nusselt's report titled: "The Ignition Velocity of Combustible Gas Mixtures" (reference 29), and finds confirmation through this measurement.

4. Detonation in the Bomb

The attempt to produce detonation in the bomb with gasoline- or benzol-air mixtures was unsuccessful. This series of tests therefore had to be made with fuel-oxygen mixtures after establishing that perfect agreement existed between the obtained diagrams for hydrogen in air- and oxygen mixtures during the pressure and the ionization-current measurement, as well as of the detonating gas mixtures. Even audition disclosed no difference in the type of noises. One such ionization current for a detonating benzol-oxygen mixture is recorded in figure 10. Although the recording speed was raised by a multiple, the current change consistently indicates a sharp break. From considerations of quality of photographs, a diagram with around 50-meters-per-second initial recording speed is reproduced as even a 400-meters-per-second initial speed, producing no dissimilar current change. In figure 10 the upper beam shows the start of the current after 25.7 millimeters. Diagram 14 gives the correlated voltage at 245 V; the voltage for the lower beam is 231 V. In figure 14, the deflection voltages were counted from the terminal voltage of the charging condenser, so that the recorded voltage can be used immediately in the calculation. The charging resistance $R = 1.83\ M\Omega$ and the condenser $C = 908\ pF$, hence a time lapse of $t = RC\ (\ln u_1 - \ln u_2) = 98 \times 10^{-6}$ second. A check on the reading is offered by the disturbance of the upper on the lower beam, visible as a small jag. The test length in this test was 220 millimeters. The result therefore, is a detonation speed of 2,250 meters per second, which agrees to within 8 percent of the computed value. The sudden flow of current also accords with theory, since for an intensity of flame front of the order of 10^{-5} millimeters, and a flame speed of 2,400 meters per second, the time lapse between start of ignition and maximum temperature amounts to 4×10^{-12} seconds. The amount of ionization current is also particularly striking; the actual flame temperature thus appears to come close to the theoretically computed.

5. Engine Knock

The ionization-current records on the detonating engine were made in the same manner. To forestall the effect of incandescent electrodes in these tests, the engine was first warmed up in normal operation, then made to knock a few engine cycles before recording, by changing the spark setting. These records (fig. 11) indicate an entirely different current change from the corresponding bomb tests. This slow current rise is the result of a slowly starting reaction at the test point. The form of combustion presents a radical departure from that of the detonation wave. According to theory and, as proved by the experiment, the ionization current rises nonuniformly at detonation. Whether the electric conductivity of the plane is attributable to thermo-ionization or whether the chemical reaction is accompanied by the creation of free ions, remains an open question. Thus, the type of the measured current flow definitely precludes the existence of a detonation wave in the engine.

The time interval for the current rise at a test point is around 3×10^{-5} seconds, according to figure 11. Figure 10 also indicates practically a short circuit of the test length by the flame, for the detonation in the bomb, since the current became maximum as against only 2/3 of the maximum value in the detonating engine; the flame has a smaller conductivity, hence a lower temperature. The last two results likewise speak against the appearance of an explosion wave in the engine.

The same current change was observed on the test electrode 1 millimeter away from the cylinder wall, as well as during violent knocking on the more distant electrodes. The test plug itself was mounted in the so-called "knock zone" of the engine. An appraisal of these records, according to flame speed, is almost impossible on account of the slow start and the pronounced scatter. Records such as figure 12 were frequently made, wherein the release of the time deflection did not occur until after response of the test electrodes. The current also discloses fluctuations attributable to the gas vibrations in the cylinder. Figure 13 illustrates, at still further increased recording speed and at lowered tensile stress, the total change of the ionization current on the detonating engine. The flame speed can still be approximately computed from some of the records. The obtained values range between + 20 meters per second, infinite (= simultaneous ignition) and - 20 meters per second. The approximate magnitude and scattering of the speed are indicative of pressure ignition, for at combustion in form of a flame front the test electrodes would have to respond in succession. The negative values point to newly created ignition centers.

Whether the compression of the residual charge and the correlated heat is the sole cause of ignition, or whether still other phenomena contribute, is impossible to decide from these few measurements.

RESULTS AND RECAPITULATION

Engine knock is, as is known, preceded by normal burning of the first part of the charge, and only the part burned last (termed, for short "residual charge"), knocks.

The aim of the present measurements was, first, to reexamine the combustion form in this residual charge, because of the absence of uniform and frequently contradictory results in the very extensive literature on the subject. On top of that, an attempt was to be made to gain a deeper insight into the mechanism accompanying the combustion process, by means of the electrical test equipment perfected within recent years.

In the literature, the point is frequently made that the residual charge ignites explosive-like - that is, at once, in its totality - while other research workers indicate merely the existence of a very high combustion speed. Because the knock manifests itself as a hard, ringing blow, it was natural to ascribe these noises to a detonation wave originating under the favorable conditions of combustion in the engine, although the short entrance length available speaks against it. Records were even published showing the detonation wave actually in close agreement with the theoretical value of the speed of propagation of 2 kilometers per second. Earlier measurements by the ionization method refute these high figures, which never exceeded 300 meters per second. A more recent high-speed motion-picture film showed that there is no such thing as flame front in the knocking residual charge, but rather the existence of ignition centers from which the ignition spreads quickly in all directions.

Since heretofore the detonation wave could not be proved with assurance except in long chambers, the experiments in the present measurements were first made in a cylindrical bomb (pipe) and then repeated with the same equipment on the engine. Three different measurements were made. The pressure measurement alone afforded no definite conclusions. On top of that, the piezoelectric pressure-recording method proved too sluggish in spite of far-reaching improvements for recording the pressure rise during detonation. The measurement of the combustion speed merely served as confirmation, since such measurements had already been made many times. Hence, a different procedure was to be followed, namely, the ionization method in conjunction with cathode-ray oscillograph, but this time not for timing the moment of arrival of the flame front but for predicting the chemical and thermal changes in the charge from the time rate of change of the ionization current. This, of course, called for a substantially higher film speed than employed up to now. Then, too, consideration of photographic recording compelled the use of photographic plates, which carried with it the difficulty of moving the cathode ray only once and at the proper instant across the light screen. A well-known hook-up somewhat modified, removed this difficulty.

The measurements in the detonating engine disclosed, first of all, a fundamentally different change of ionization current from that of detonating-gas mixtures, from which it is safe to say that no detonation wave occurs in the knocking engine.

On top of that, the type of current introduction points toward a slowly starting chemical, and perhaps an exothermic process, beginning after completed compression in the whole residual charge, and tending steadily toward its maximum value. That the slow rise of conductivity of the charge cannot be caused by heat of compression, has been proved.

Since the temperature and the carburetion differ in the combustion chamber with respect to time and place, the moment and the place of the first ignition are subject to chance. It results in ignition centers from which the ignition spreads in all directions. Through such ignition centers the observed negative flame speeds and their pronounced scatter can be readily explained. An almost closed flame front, such as exists in the normal combustion, is therefore nonexistent in the knocking residual charge.

To the extent that these measurements themselves permit of any conclusion, autoignition of the charge residue takes place in the knocking engine because its ignition is only in indirect relationship with the ignition initiated by the spark plug or the preceding flame front. Since the pressure rise and the heat connected with it ultimately cause the ignition, the pressure ignition is, as special form of autoignition, the cause of the knock. It is, of course, conceivable that other than the pressure electric phenomena, heat radiation, or other still unknown factors might act on the speed of chemical transformation. The effect of antiknocks, particularly, might be explained as retarding the first start or lowering the rate of chemical reaction at first, and so giving the flame front a chance to speed through the residual charge before this is ignited by pressure ignition.

Since the total residual charge is ready to ignite by the time the first ignition centers occur, the ignition spreads uncommonly fast, creating a zone of high pressure which moves toward the spark plug and even up to the point where the combustion had been delayed as a result of cooling. As such a pressure disturbance is reinforced in its front during its advance, it might be that this causes the knocking noises on arrival at a rigid wall; similarly as the present measurements indicate it for the detonation wave. This wave also dies out at the combustion-chamber walls after repeated reflection. Then the power decrease is the result of the increased heat transfer on the wall, caused by the motion of the gas mass, the temporarily increased pressure at the reflection of the gas vibrations, and the turbulence connected with in.

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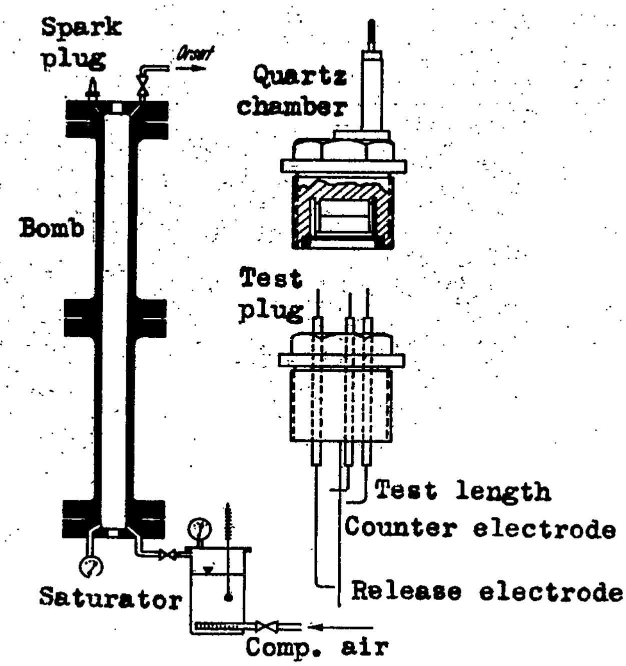

Figure 1.- Experimental layout.

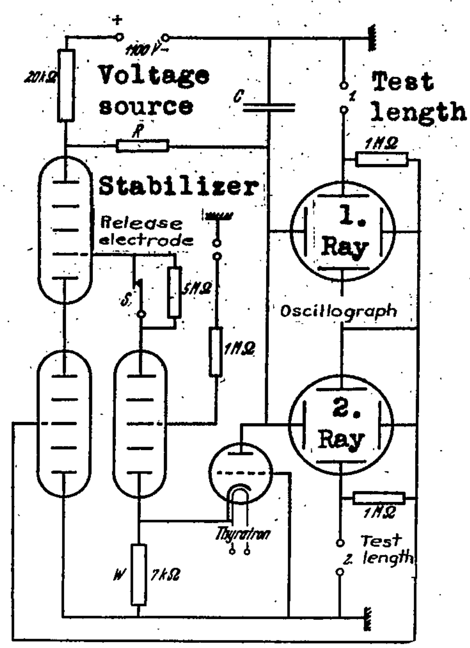

Figure 7.- Hook up of test arrangement.

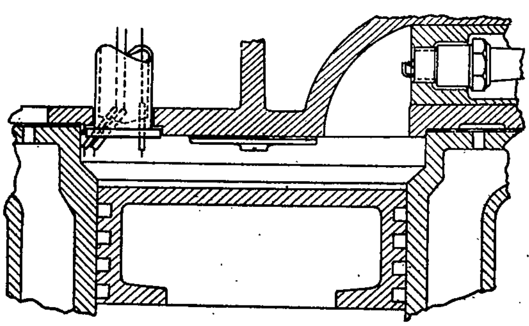

Figure 6.- Combustion chamber of test engine.

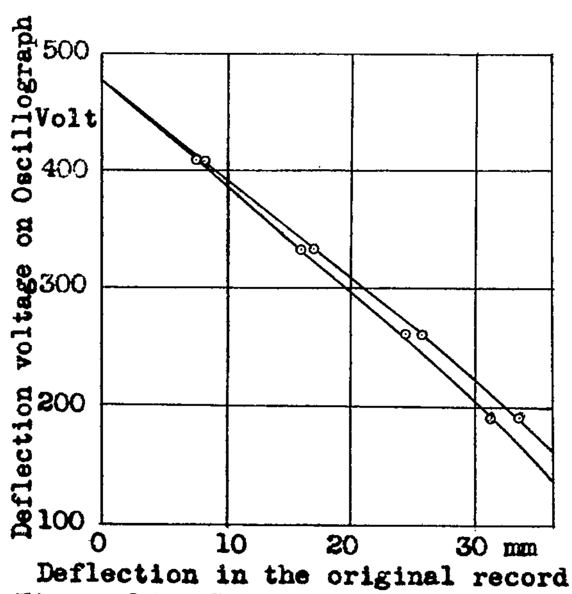

Figure 14.- Test record of Oscillograph (the top line corresponds to the lower ray of record 7 to 12.)

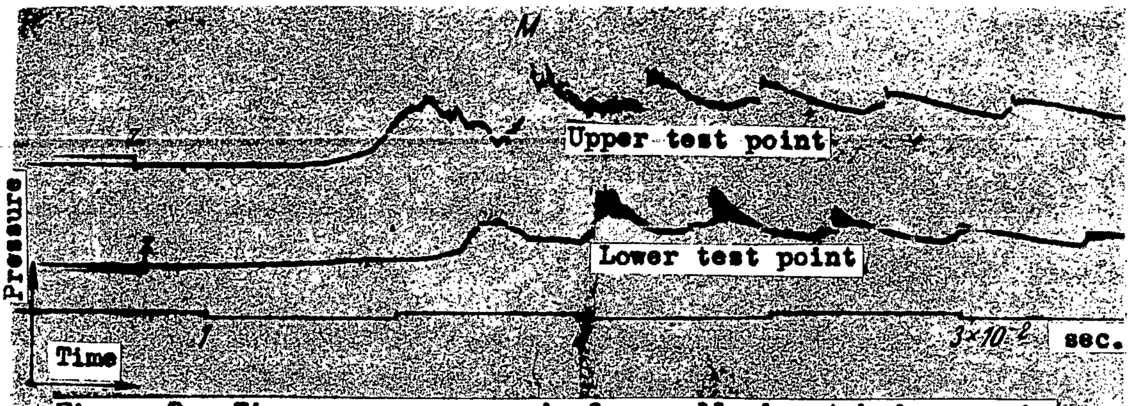

Figure 2.- Time-pressure record of normally burnt hydrogen-air mixture in the bomb; p^{charge} =1 atm.

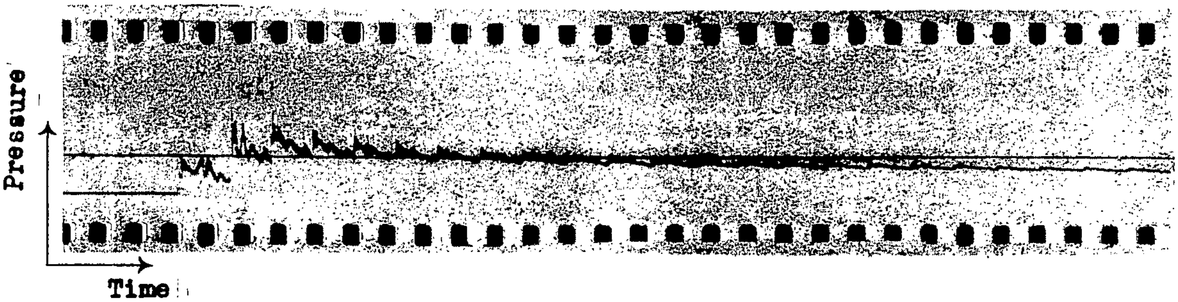

Figure 3.- Time pressure record of normally burnt hydrogen-air mixture in the bomb at charging pressure p_1 =3 atm.; taken at lower test point.

Figure 5.- Pressure-time record of detonating engine. ϵ=7.5:1; n =1070; 70% load.

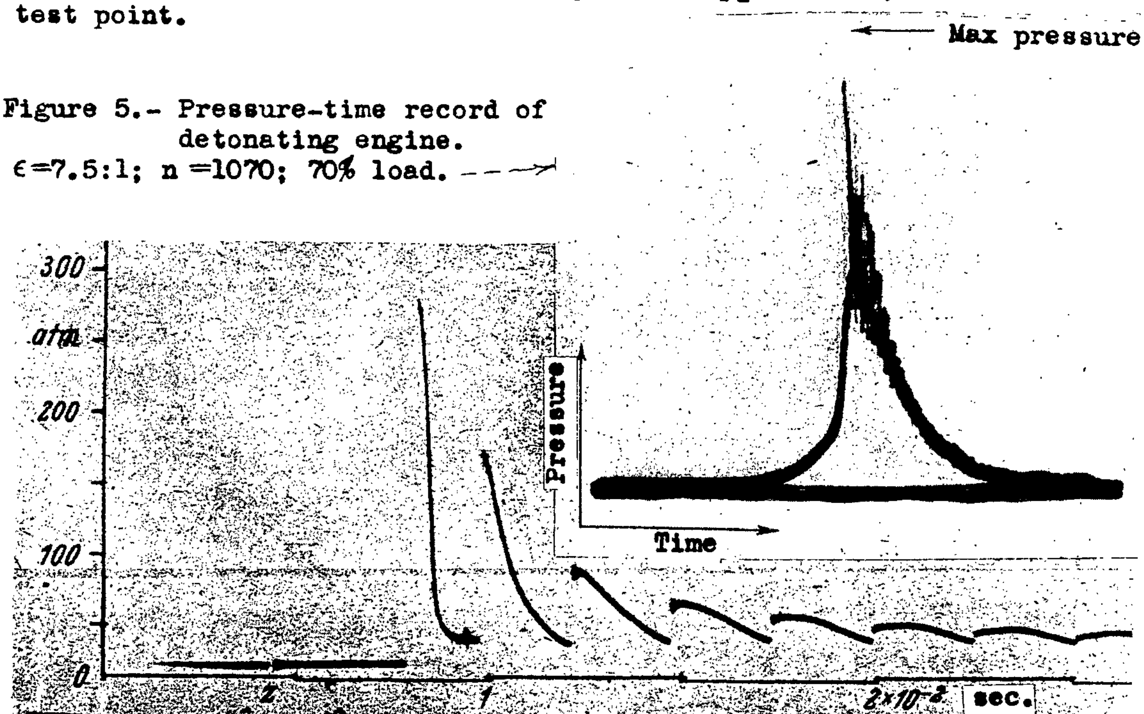

Figure 4.- Pressure-time record of detonating hydrogen-air mixture in the bomb at 8 atm. charging pressure on the lower test point.

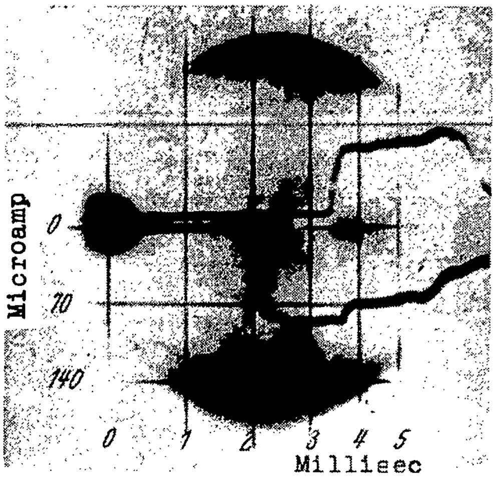

Figure 8.- Normal combustion in the bomb.

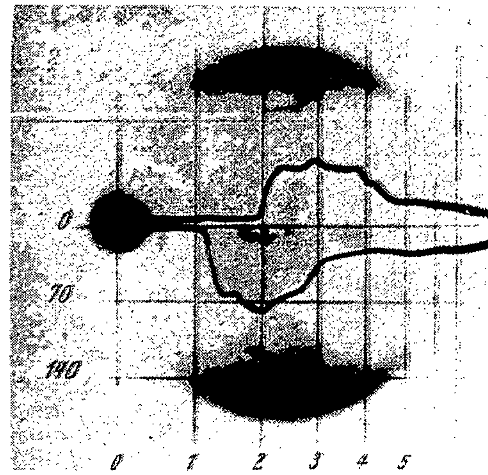

Figure 9.- Normal combustion in the engine.

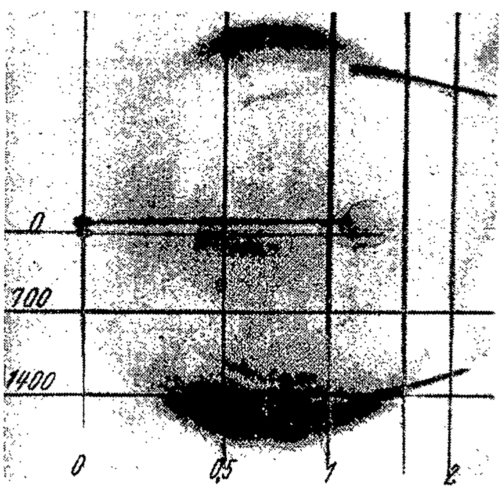

Figure 10.- Detonation in the bomb

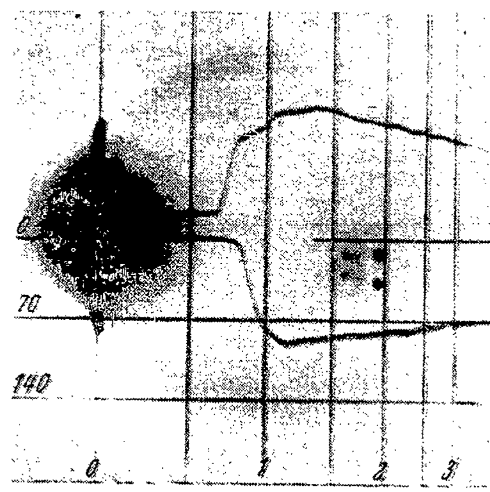

Figure 11.- Knock in the engine.

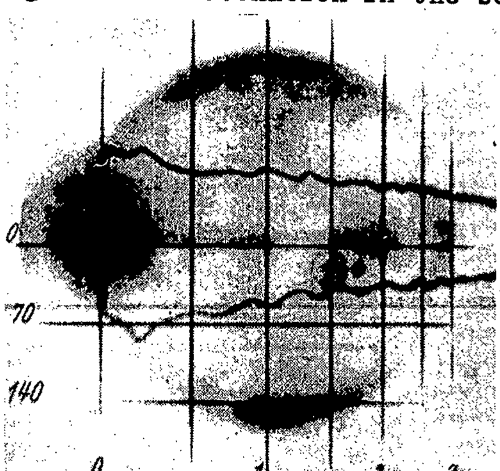

Figure 12.- Knock in the engine.

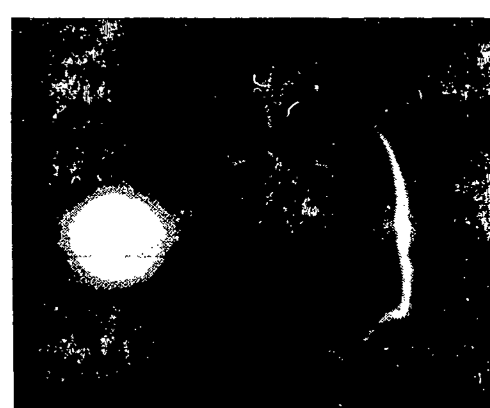

Figure 13.- Knock in the engine.